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Refining the Spectroscopic Orbit of the Massive Binary Star Spica

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Refining the Spectroscopic Orbit of the Massive Binary Star Spica

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Abstract

The purpose of this research is to create an accurate simulation of the binary star, Spica, to determine the internal structure of the primary star. A Bayesian Markov Chain Monte Carlo code, called EXOFAST, has been edited and utilized to find the best-fit parameters to describe the orbit of Spica. The specific target for this paper is the derivation of the apsidal period of the star system, which will lead to the derivation of the internal structure of the primary star. Six radial velocity data sets obtained between 1889 and 2000 were analyzed, yielding an apsidal constant of 139.0 ± 6 years, with 68% confidence, which is consistent with the value of Herbison-Evans et. al. (1971), of 124 ± 11 years.

I. Introduction

Spica was discovered to be a binary star in 1891 from observations by Vogel (1891). In the 1970s, astronomers were able to use an intensity interferometer to resolve the two stars (Spica A and B) and determine certain orbital parameters, such as the inclination, the semi-major axis, etc. Figure 1 below shows a representation of some of the other orbital parameters being simulated.

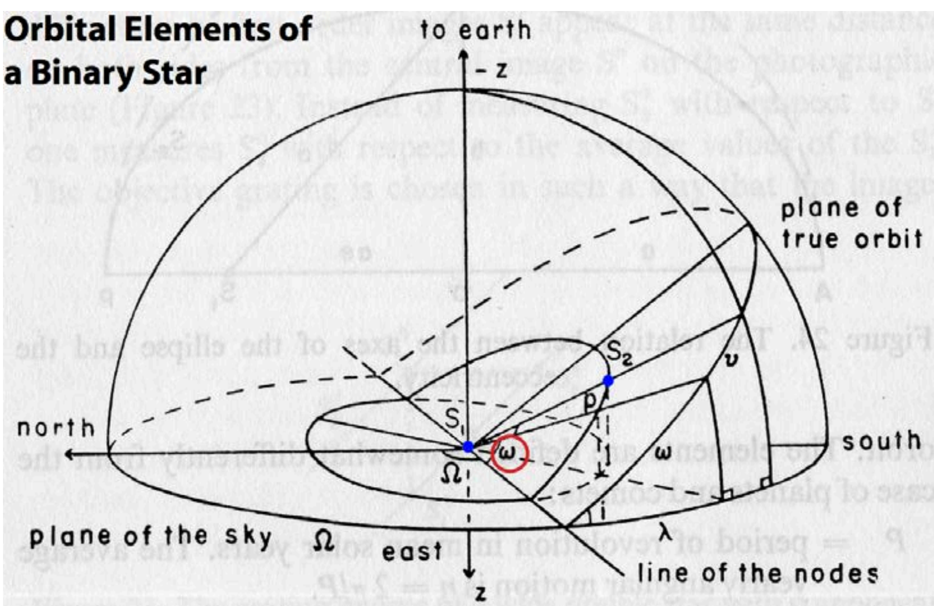

Figure 1: A diagram that shows the orbital parameters that are used to describe binary star systems. Ω is the position angle of the line of nodes, ω is the longitude of periastron, υ is the angle from the passage of periastron, and the S1 and S2 are Spica A and B respectively (Binnendijk, 1960).

The astronomers had also detected apsidal motion, which meant that Spica's components could not be spherically symmetric. The fact that they are not spherically symmetric is due to their rapid rotation and tidal interaction. The system's period is about 4.014 days; Spica A is about 10.4 and Spica B is 7.1 times the mass of our sun (Aufdenberg et al., 2008). With these parameters, Spica A is oblong, with the more extended part being pulled towards Spica B (Figure 2).

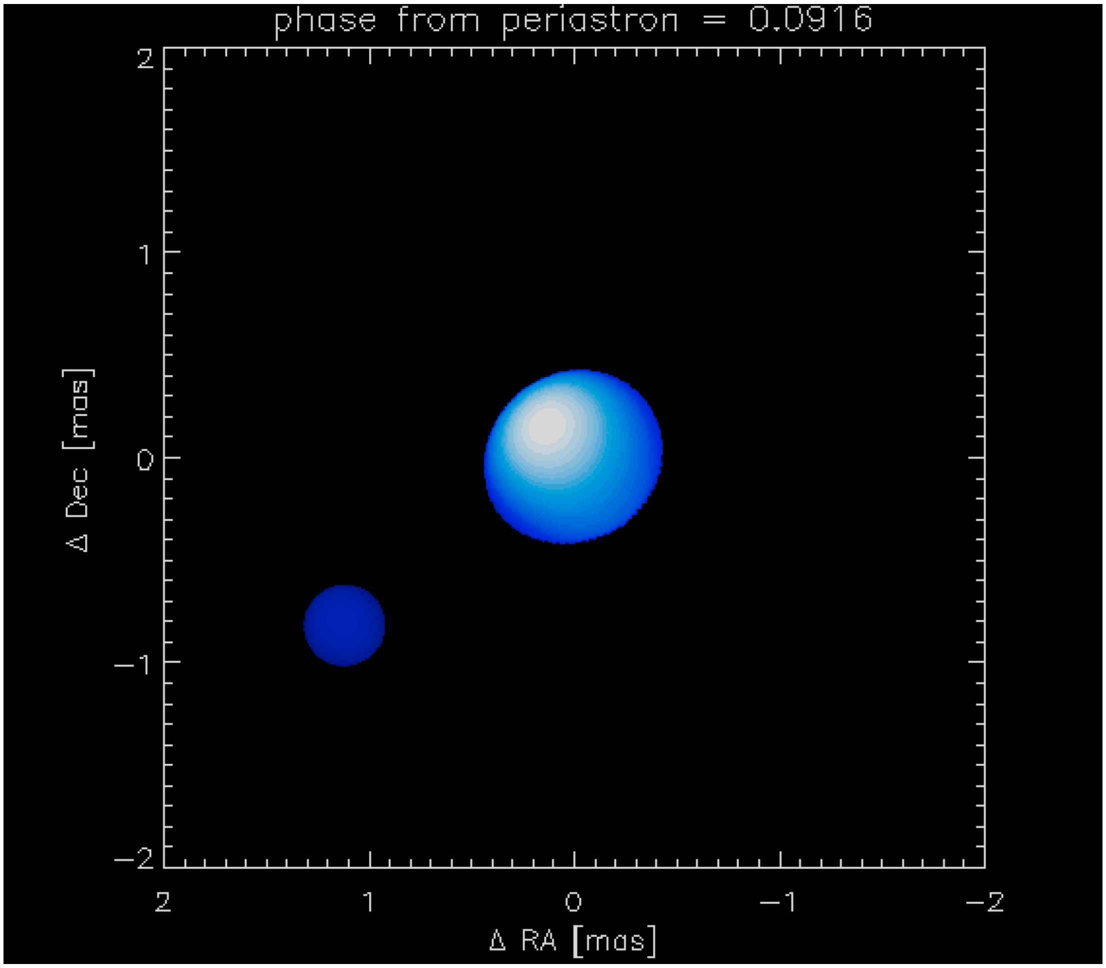

Figure 2: A model of the Spica system using IDL. Aufdenberg (2008) plotted the system using his code, which only changed one value of one parameter at a time. This made it difficult to constrain certain parameters using his code. Note the pull that Spica B has on Spica A. Also, the system shows signs of gravity darkening, which is the effect that is caused by a star rotating so rapidly that it has an oblate spheroid shape. Spica A also shows signs of the phenomenon of limb darkening that causes the center of the star to appear brighter than the edge of the image.

In 1973, the observed value of the apsidal constant was found to differ from the theoretical value by a factor of three (Mathis and Odell, 1973). In 2007, two more interferometers, SUSI (Sydney University Stellar Interferometer) and CHARA (The Center for High Angular Resolution Astronomy), were used to collect data from the system. These new data were much more accurate than the previous data and caused a revision in the best estimates for the semi-major axis and the inclination. To consider the revision of all the orbital parameters, a code is needed that can accurately fit the data and provide best fit values and uncertainties for each of the parameters.

II. Methodology

A method for finding a solution to this problem is to use the statistical method of Differential Evolution Markov Chain Monte Carlo. The EXOFAST program originally used this method and already existed as a fully functional and accurate code, but it was used for calculating the orbital parameters of a transiting planet and host star (Eastman et al., 2013). Spica B replaced the transiting planet, which required EXOFAST and its functions to be altered to add the secondary radial velocity and the apsidal period to the code. The priors, shown in Figure 3, chosen for the simulation, were taken from Dukes's (1974) observations and analysis.

PRIOR VALUES AND WIDTHS

Parameter	Units	Value
e	Eccentricity	0.13 ± 0.06
ω_0	Argument of periastron at T_0 (degrees)	129 ± 21
U	Apsidal Period (years)	124 ± 40
P	Period (days)	4.015 ± 0.001
$e\cos\omega_0$ ..	....	-0.08 ± 0.05
$e\sin\omega_0$ ..	....	0.10 ± 0.06
T_0	Time of periastron (BJD_{TDB})	2440690.05 ± 0.07
K_1	Primary RV semi-amplitude (km/s)...	116 ± 6
K_2	Secondary RV semi-amplitude (km/s)	196 ± 20
γ_1	Primary systemic velocity (km/s)	0 ± 3

Figure 3: The prior values from Dukes's (1974) observations.

Measurements from Vogel (1889), Baker (1910), Struve & Ebbighausen (1934), Struve et al. (1958), Shobbrook et al. (1972) and Riddle (2000) provide 340 and 228 RV measurements for the primary and secondary stars respectively. Eleven radial velocity measurements of the secondary star from Riddle (2000) were dropped from the analysis due to very high residuals (> 35 sigma).

III. Results

The final model shown here was produced by running a 24 Markov chain simulation with 100,000 steps. Fitting the data yielded a median apsidal period of 139 ± 6 years with 68% confidence, which is consistent with the value of Herbison-Evans et al. (1971), 124 ± 11 years. Error bars shown in the global fit were scaled within the EXOFAST code by a factor of 3.4 from the literature values to achieve a reduced chi squared value of 1.0. The simulation produced accurate radial velocity curves and orbital elements along with posterior distributions and covariances for each element. The ratio of the orbital period to the apsidal period (P/U), one of three parameters needed to determine the observational apsidal-motion constant k_{2obs}, (Claret & Willems, 2002), is now constrained to 5%, P/U = 7.91±0.36x10-5. $k2_{obs}$ also depends linearly on the mass ratio which we constrain to 1%, $M_2 / M_1 = 0.622 \pm 0.005$. The eccentricity is constrained in our solution to 4%, e = 0.116±0.004, but is inconsistent with the value of Riddle (2000), e=0.067±0.014, based on the primary star alone. The uncertainty in the apsidal constant is dominated by the uncertainty in the ratio of the primary star radius, R_1 to the semi-major axis, a, proportional to $(R/a)^5$. The semi-major axis can be found from a*sini = 23.14±0.88 R_{sun}, constrained to 4%. Figure 4 shows the results for the orbital elements.

Final Orbital Elements

MEDIAN VALUES AND 68% CONFIDENCE INTERVAL

Parameter	Units	Value
RV Parameters:		
e	Eccentricity	$0.1164^{+0.0039}_{-0.0038}$
ω_0	Argument of periastron at T_p	137.3 ± 2.8
U	Apsidal Period (years)	$139.0^{+6.4}_{-5.9}$
P	Period (days)	4.014518 ± 0.000013
asini	Projected semi-major axis (AU)	$0.1080^{+0.0036}_{-0.0035}$
$e\cos\omega_0$ ..	....	-0.0855 ± 0.0046
$e\sin\omega_0$ ..	....	$0.0788^{+0.0051}_{-0.0052}$
T_P	Time of periastron (BJD_{TDB})	$2440690.577^{+0.057}_{-0.056}$
K_1	Primary RV semi-amplitude (km/s) ..	119.63 ± 0.71
K_2	Secondary RV semi-amplitude (km/s)	192.18 ± 0.86
M_2/M_1 ..	Mass ratio	0.6225 ± 0.0047
γ_1	Primary systemic velocity (km/s)	-2.48 ± 0.42

Figure 4: The final orbital elements produced by EXOFAST.

Figure 5 shows the posterior distributions of the orbital elements.

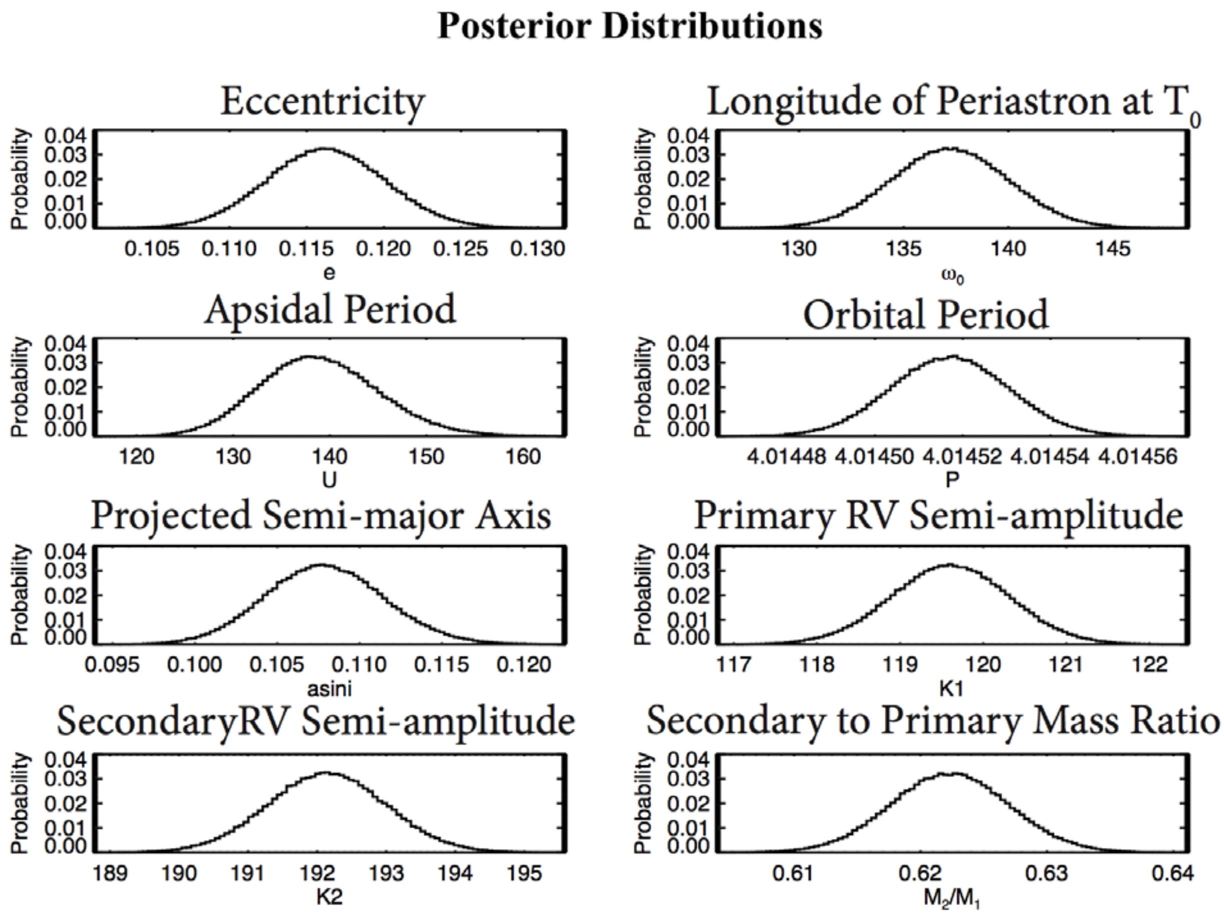

Figure 5: The posterior distributions from a 24 Markov chain simulation with 100,000 steps.

The covariances are shown in Figure 6. Each variable is compared with every other variable used. The negative numbers mean that the variables are negatively correlated.

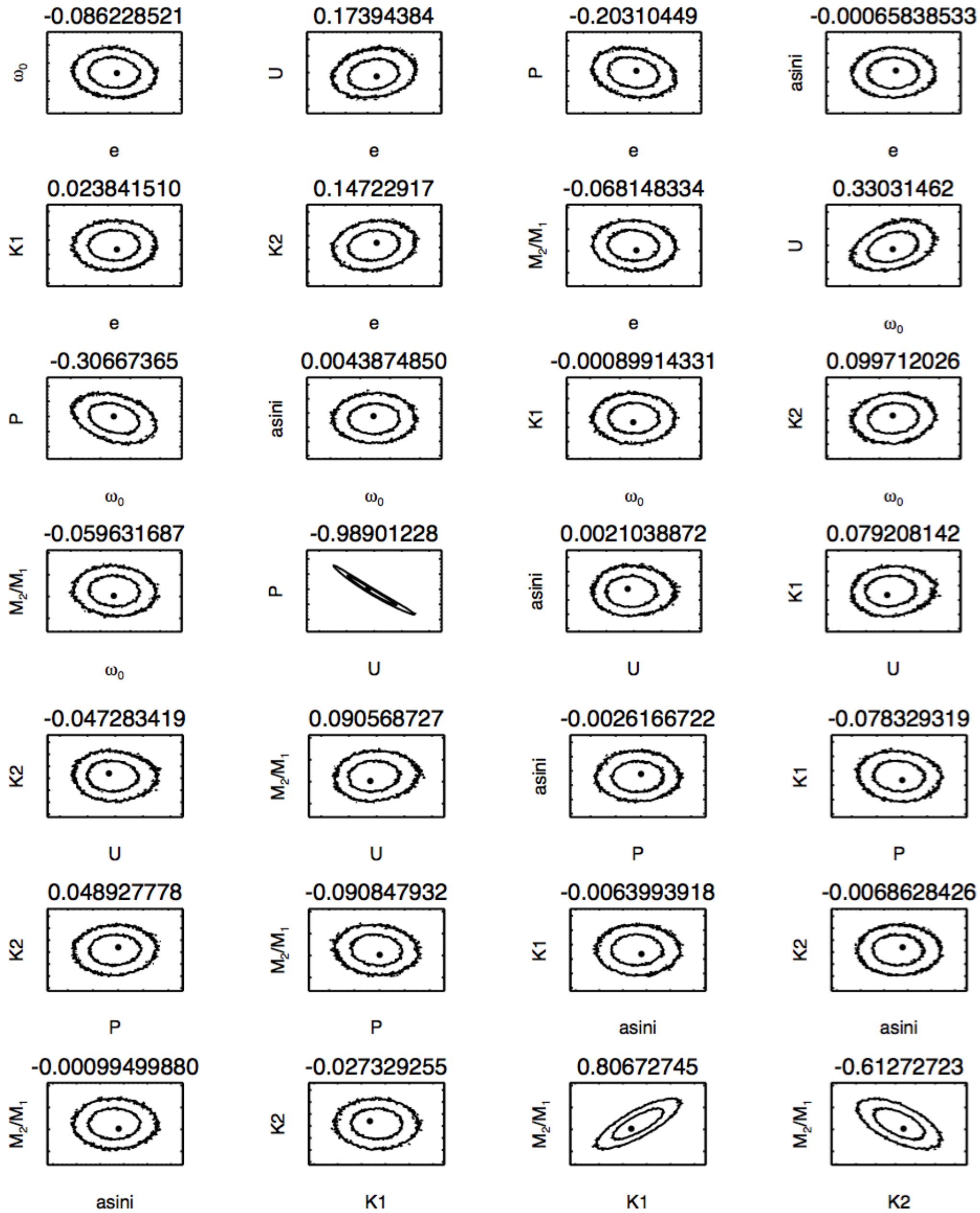

Figure 6: The covariances from a 24 Markov chain simulation with 100,000 steps.

Figure 7 shows the radial velocity curve for Vogel data from 1889. Unfortunately, Vogel was only able to resolve the primary star's radial velocity, so the fit is only for the primary star. The observed data along with the respective error bars are the points, and the fit to the data is denoted by the solid line. Note that as the time advances for these graphs, the maximum and minimum of the graphs is slowly changing. This is the obvious evidence of the system having an apsidal period.

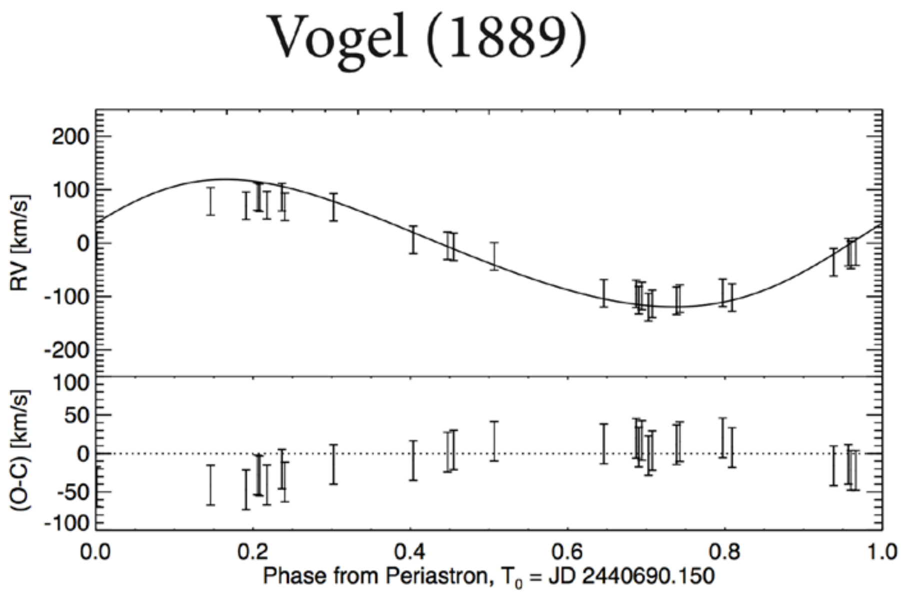

Figure 7: Radial velocity fit for Vogel data.

Figure 8 shows the radial velocity curves for Baker data from 1910. These observations were the first to show accurate radial velocities for both the primary and secondary star. The primary star's radial velocity and simulated fits are shown in black, while the secondary's is shown in red.

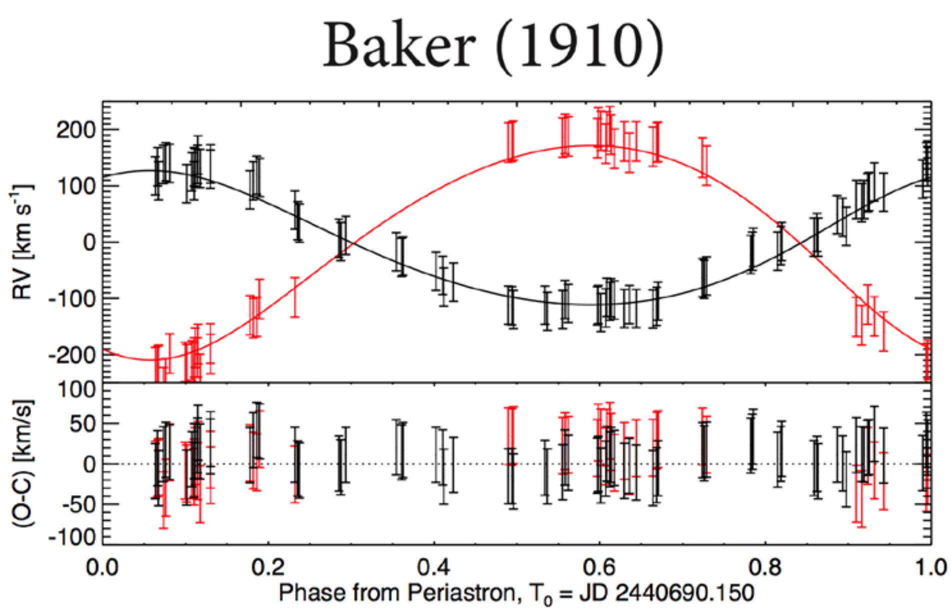

Figure 8: Radial velocity fits to Baker data.

Figure 9 shows the radial velocity fits for the Struve and Ebbighausen data.

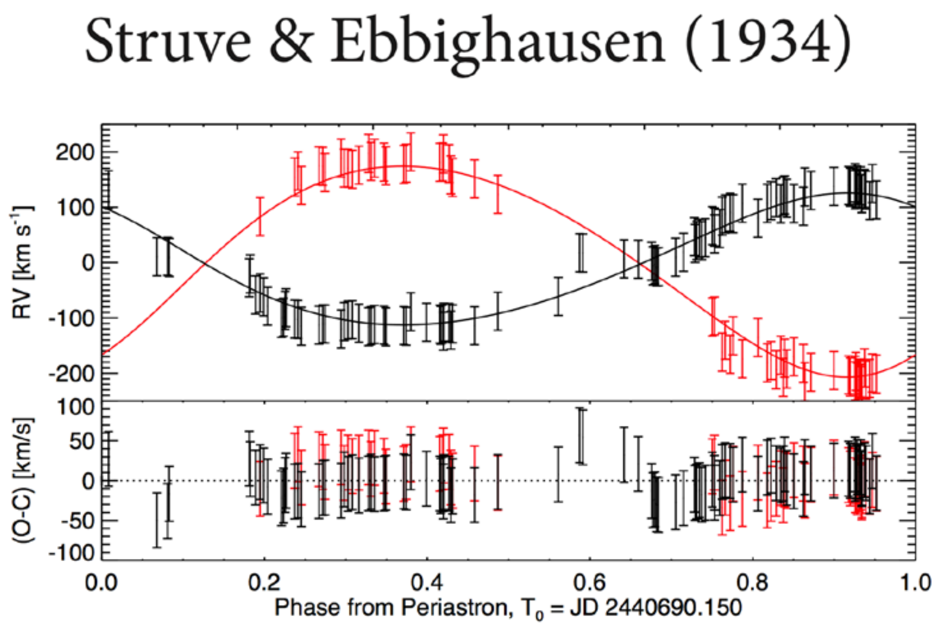

Figure 9: Radial velocity fits to the Struve and Ebbighausen data.

Figure 10 shows the radial velocity fits for the Struve data.

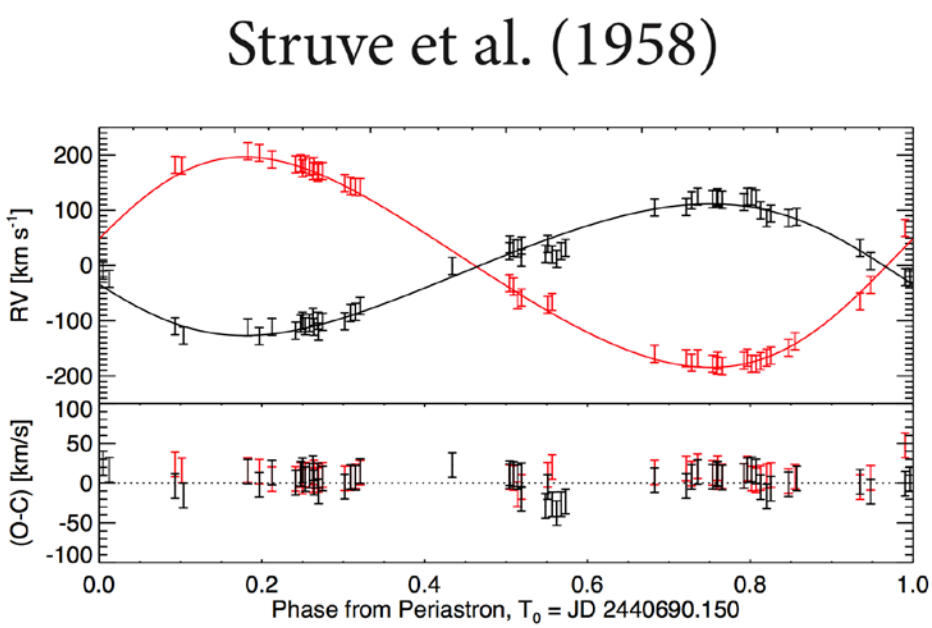

Figure 10: The radial velocity fits for the Struve data.

Figure 11 shows the radial velocity fits for the Shobbrook data. The majority of the data taken here were close to the maximum and minimum because they were looking for the β Cephei nature of the primary star.

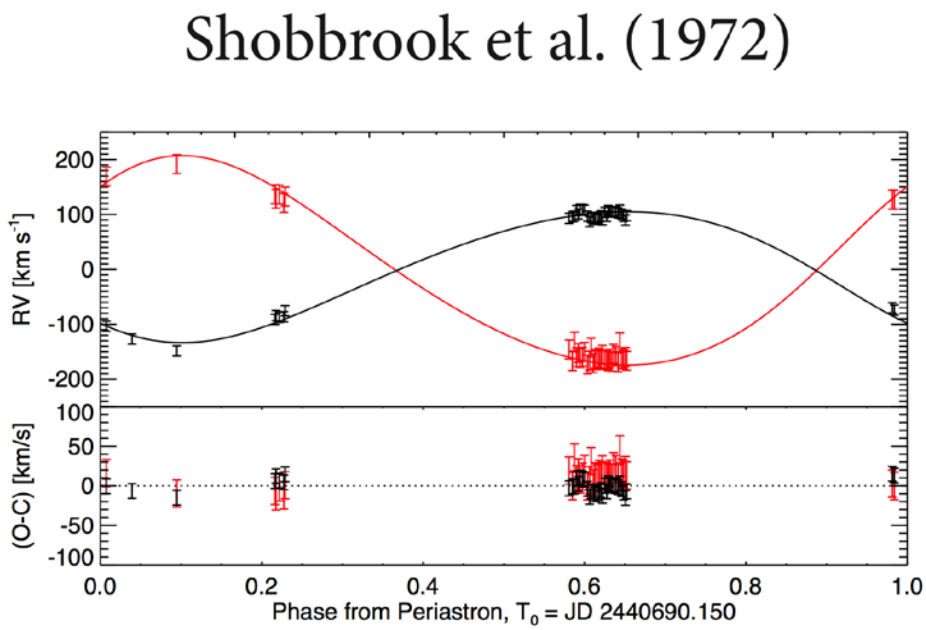

Figure 11: The radial velocity fits for the Shobbrook data.

Finally, Figure 12 shows the radial velocity fits for the Riddle data.

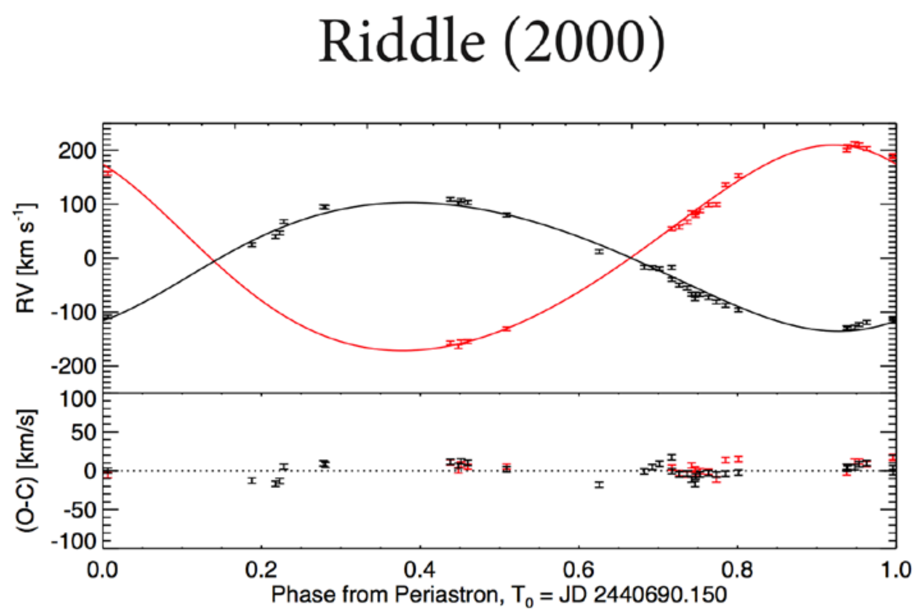

Figure 12: The radial velocity fits for the Riddle data.

IV. Discussion

This model of the Spica system has produced an accurate value for the apsidal period, which will be used to estimate the internal structure of the primary star. Once the internal structure is completely defined, the model will be compared with a model produced by a team of astroseismologists who are attempting to solve the same problem with a different approach. If the two models agree, it will imply that both models are accurate and will be able to be used on other binary star systems. Some of the methods could even be used on other stars or other astrophysical fields of study. For future studies, there will need to be higher precision radial velocity data taken to resolve some of the discrepancies between this model and previous models. The next step to constrain the internal structure of the primary star is to constrain the inclination of the orbit. The light curve and interferometry analysis to do so are currently underway.

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